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**REDUCTION OF A LARGE-SCALE GLOBAL MOBILITY OPTIMIZATION MODEL THROUGH AGGREGATION**


by

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This thesis develops a two-stage aggregation/ disaggregation model based on THRUPUT2 (Morton, Rosenthal and Lim, 1995), a mobility optimization model used to analyze the ability of the Armed Forces of the United States to conduct airlifts in support of major military operations. For a given fleet of aircraft, a given network of routes, and a given set of unit movement requirements over time, THRUPUT2 schedules airlift to minimize late deliveries and non-deliveries. The linear programming model presented is based on THRUPUT2, but aggregates those units which share the same origin-destination pair and have overlapping time periods and therefore creates a smaller linear program. This reduction in size will consequently decrease the time needed to solve, which is desirable because repeated runs of this model are necessary to generate analytic insight and develop recommendations. The thesis further develops a disaggregation model which will remove the aggregations of the first, and therefore offer resolution similar to that of THRUPUT2.

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# REDUCTION OF A LARGE-SCALE GLOBAL MOBILITY OPTIMIZATION MODEL THROUGH AGGREGATION

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# ABSTRACT

This thesis develops a two-stage aggregation/ disaggregation model based on THRUPUT2 (Morton, Rosenthal and Lim, 1995), a mobility optimization model used to analyze the ability of the Armed Forces of the United States to conduct airlift in support of major military operations. For a given fleet of aircraft, a given network of routes, and a given set of unit movement requirements over time, THRUPUT2 schedules airlift to minimize late deliveries and non-deliveries subject to physical and policy constraints. The linear programming model presented is based on THRUPUT2, but aggregates those units which share the same origin-destination pair and have overlapping time periods, thereby creating a smaller linear program. This reduction in size will consequently decrease the time needed to solve, which is desirable because repeated runs of this model are necessary to generate analytic insight and develop recommendations. The thesis further develops a disaggregation model which will remove the aggregations of the first, and therefore offer resolution similar to that of THRUPUT2.

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# EXECUTIVE SUMMARY

This thesis develops a two-stage aggregation/disaggregation model based on THRUPUT2 (Morton, Rosenthal and Lim, 1995), a mobility optimization model developed at the Naval Postgraduate School for the Air Force Studies and Analysis Agency (AFSAA). Throughput II is used to analyze the ability of the Armed Forces of the United States to conduct airlift in support of major military operations. For a given fleet of aircraft, a given network of routes, and a given set of movement requirements over time, THRUPUT2 schedules airlift to minimize late deliveries and non-deliveries subject to physical and policy constraints.

The first of the two models developed is the Unit Aggregation Model. This model is based on THRUPUT2, but aggregates those units which share the same origin-destination pair and have overlapping time periods. This aggregation reduces the size of the model. This reduction in size will consequently decrease the time needed to solve the model. Because repeated runs of this model are necessary to generate analytic insight and develop recommendations, this time savings can be very helpful. However, this time savings is not without cost. The aggregation causes a loss of model fidelity at the unit level. This loss of resolution can be partially recovered through the use of a disaggregation model.

The disaggregation model removes the aggregations of the Unit Aggregation Model. It achieves this goal by

assigning unit equipment and troops to those delivery missions scheduled by the Unit Aggregation Model. The resolution is therefore similar to that of THRUPUT2.

The Unit Aggregation Model's size is reduced to about 10% that of THRUPUT2's size for a realistic scenario involving two major regional contingencies. For this scenario, the aggregation/disaggregation model combination takes twenty minutes to generate and solve using GAMS/OSL software on an IBM RS6000/590 computer. THRUPUT2 takes about three hours to generate and solve with the same computer and software.

# I. INTRODUCTION

## A. BACKGROUND OF THRUPUT2

Operations Desert Shield and Desert Storm revealed deficiencies in tools for planning and analyzing air mobility during Major Regional Contingencies (MRCs). After these operations, the United States Air Force Studies and Analysis Agency (USAF/SAA) began examining the use of optimization in the development of a set of such tools. Efforts in global airlift optimization began at the Naval Postgraduate School in Fiscal Year 1994 with funding from USAF/SAA. These efforts continue to the present time.

In 1994, the work sponsored by USAF/SAA resulted in the THRUPUT2 time-phased global airlift mobility model which was developed during thesis research by Captain Lim Teo-Weng, Singapore Air Force (Lim, 1994). In adding a desired time dimension, Captain Lim's model expanded upon the original THRUPUT - a static model developed by Major Kirk Yost, USAF (Yost, 1994).

## B. PROBLEM

THRUPUT2 is a very large linear program due to the huge number of units associated with "real life" scenarios. Recently, for a data set modeling a two MRC scenario, THRUPUT2 took over three hours to generate and solve using GAMS (Brooke *et al.*, 1992) software on an IBM RS6000 computer. Furthermore, this data set was made solvable only by aggregating time periods into steps of two days. The

larger these scenarios are, the more time and memory required to solve the model.

## C. GOAL

The purpose of this thesis is to make the model smaller and, consequently, reduce the time to solve a given scenario. If the model's size can be sufficiently reduced, time aggregation of the model will be unnecessary.

## D. METHODOLOGY

The THRUPUT2 formulation (given in Appendix A) contains many variables and constraints that are indexed over units. The model will be smaller if we aggregate into "groups" those units that share origin/destination pairs and have overlapping delivery windows. This treatment requires a reformulation of the current THRUPUT2 model.

The new model will have some limitations. THRUPUT2 had a penalty in the objective function for late deliveries. This feature must be removed from a unit aggregation model because we will not be able to tell which particular unit within a group is having its cargo or troops delivered during an arbitrary time period. Further, the new model will use a weighted cargo density for each group of units. By reducing the densities for those units in a group that have greater densities, this weighting can potentially allow a group to move cargo which would not be movable in THRUPUT2.

To ameliorate the differences in solutions caused by this unit aggregation, we will also develop a second model

which will remove the first model's aggregations. Because only aircraft loading decisions will be necessary for the disaggregation, this secondary model will be a much smaller model than the original THRUPUT2 model, which had to make both loading and aircraft scheduling decisions. This model will incorporate the lateness penalty in its objective function and will use unweighted densities for each unit. While the disaggregation model will require additional time to solve, the time required to generate and solve the Unit Aggregation/Disaggregation Model combination will be less than the time to generate and solve using THRUPUT2.

## E. JUSTIFICATION

Analysts need to run the model many times in order to evaluate such things as different fleet mixes. The time required to solve the model thus becomes a factor in either the quality or timeliness of this analysis. Furthermore, if the model can be made sufficiently small, we can dispose of the time aggregation mentioned previously.

# II. UNIT AGGREGATION MODEL

## A. OVERVIEW

The Unit Aggregation Model is largely based on the Morton, Rosenthal, and Lim (1995) THRUPUT2 (Appendix A). Like THRUPUT2, the aggregation model has constraints for the following categories: demand satisfaction, aircraft balance, aircraft capacity, aircraft utilization, and airfield capacity. These constraints are modified to reflect the aggregation of units into groups. The Unit Aggregation Model also contains additional constraints which limit delivery. These are referred to as maximum delivery constraints. The objective function of the model will maximize delivery of unit equipment (UE) and passengers (PAX).

## B. GROUP FORMATION

The Unit Aggregation Model requires the formation of groups. Those units that share the same origin-destination pair and have overlapping delivery windows form a group. Figure 1 shows the delivery windows for six units with the same origin and destination. Note that the delivery windows of Units A, B, E, and F overlap at least one of the other unit's delivery window, while Units C and D only overlap each other's window. Thus, Group 1 consists of member Units A, B, E, and F and Group 2 contains Units C and D.

It would be inappropriate to allow an individual unit's delivery window to expand to the window of its group. The

Unit Aggregation Model helps prevent this from happening with some new constraints called Maximum Delivery constraints. The complete formulation is presented in the next section.

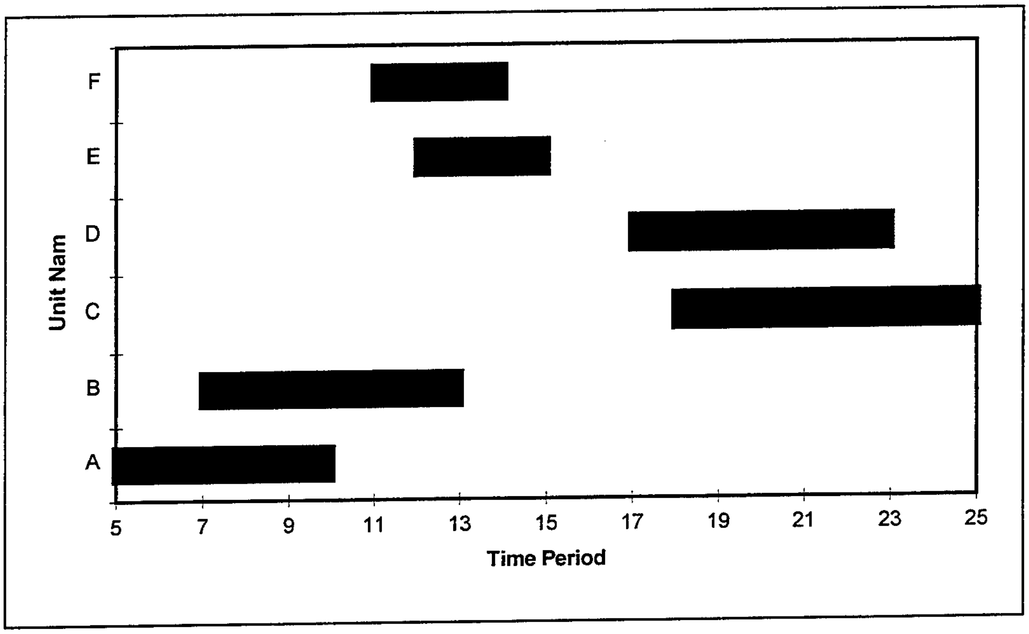


Figure 1. Delivery windows for six different units having the same origin-destination pair.

## C. MATHEMATICAL FORMULATION OF UNIT AGGREGATION MODEL

### 1. Indices

| | |
|---|---|
| $u$ | units, e.g., 82nd Airborne |
| $g$ | groups of units |
| $a$ | aircraft types, e.g., C5, C17 |
| $t, t'$ | time periods |
| $b$ | airfields (a/f) in general |
| $r$ | routes |

## 2. Index Sets

### a. *Airfield Index Sets*

$B$ set of all airfields

$I \subseteq B$ origin airfields

$K \subseteq B$ destination airfields

### b. *Aircraft Index Sets*

$A$ set of all aircraft (a/c) types

$A_{bulk} \subseteq A$ a/c capable of carrying only bulk-sized cargo

$A_{over} \subseteq A$ a/c capable of carrying bulk- and over-sized cargo, but not out-sized

$A_{out} \subseteq A$ a/c capable of carrying bulk-, over-, and out-sized cargo

### c. *Route Index Sets*

$R$ set of all routes

$R_a \subseteq R$ permissable routes for a/c type *a*

$R_{ab} \subseteq R_a$ permissable routes for a/c type *a* that use a/f *b*

$R_{au} \subseteq R_a$ permissable routes for a/c type *a* which have an appropriate origin *i* and destination *k* for unit *u*

$DR_i \subseteq R$ delivery routes that originate from origin *i*

$RR_k \subseteq R$ recovery routes that originate from destination $k$

### d. *Time Index Sets*

$T$ set of all time periods

$T_{gar}$ possible launch times of missions for group $g$ using a/c type $a$ and route $r$

$AT_u$ all days in delivery window for group to which unit $u$ belongs prior to the unit's ALD

$DT_{uar}$ all days in delivery window for the group to which unit $u$ belongs prior to the ALD of the next unit available for loading

$RT_{uar}$ all days in delivery window for group to which unit $u$ belongs in which UE/PAX may be sent along route $r$ on a/c type $a$ and arrive at the destination by unit $u$'s RDD

### e. *Unit Index Sets*

$U$ Set of all units

$U_g \subseteq U$ All units which belong to group $g$

$RPR_{gu} \subseteq U_g$ All units belonging to group $g$ which have an RDD prior to or the same as unit $u$'s RDD

$APA_{gu}$ All units belonging to group $g$ which have an ALD prior to unit $u$'s ALD

$First_g$ The unit belonging to group *g* having the earliest ALD

### 3. Data

#### a. *Movement Requirement Data*

$MovePAX_u$ PAX (in 100s) to be moved for unit *u*

$MoveUE_u$ UE (in 100 stons) to be moved for unit *u*

$ProBulk_u$ proportion of unit *u* UE that is bulk-sized

$ProOver_u$ proportion of unit *u* UE that is over-sized

$ProOut_u$ proportion of unit *u* UE that is out-sized

#### b. *Penalty Data*

$NoGoPenUE_u$ Non-delivery penalty (per ston) for unit *u* equipment

$NoGoPenPAX_u$ Non-delivery penalty (per troop) for unit *u* PAX

$Preserve_{at}$ Penalty (small artificial cost) for keeping a/c type *a* in mobility system at time *t*

#### c. *Cargo Data*

$UESqFt_u$ Average floor space requirement per ston of UE from unit *u*

$PAXWt_u$ Average weight (in stons) of one troop from unit *u*, including personal equipment

### d. *Aircraft Data*

$Supply_{at}$ Number of a/c type *a* that become available at time *t*

$MaxPAX_a$ Maximum allowed PAX on a/c type *a*

$PAXSqFt_a$ Average square footage (in sq. ft.) used by a unit *u* troop for a/c type *a*

$ACSqFt_a$ Available floor space (in sq. ft.) for a/c type *a*

$LoadEff_a$ Cargo space loading efficiency ($\leq 1$) for a/c type *a*

$URate_a$ Established utilization rate (flying hours per a/c per day) for a/c type *a*

### e. *Airfield Data*

$MOGCap_{bt}$ A/C handling capacity (in narrow-body equivalents) at airfield *b* in time *t*

$MOGReq_{ab}$ A/C handling capacity consumed by one a/c type *a* at airfield *b*

$MOGEff_{bt}$ MOG efficiency factor ($\leq 1$)

### f. *Aircraft Route Data*

$MaxLoad_{ar}$ Maximum payload (in stons) for a/c type *a* along route *r*

$FltTime_{ar}$ Flying hours consumed by a/c type *a* along route *r*

$GTime_{abr}$ Ground time for a/c type *a* at a/f *b* flying route *r*

$DTime_{abr}$ Cumulative time (flying time and ground time) taken by a/c type *a* to reach a/f *b* on route *r*

$CTime_{ar}$ Cumulative time (flying and ground time) taken by a/c *a* to fly route *r*

**4. Variables**

$X_{gart}$ Number of a/c type *a* flying route *r* with start time *t* airlifting group *g*

$Y_{art}$ Number of a/c type *a* recovering along route *r* with start time *t*

$ALLOT_{ait}$ Number of a/c type *a* allocated to origin *i* in time *t*

$RELEASE_{ait}$ Number of a/c type *a* allocated to origin *i* in time *t-1* but not scheduled for any missions from time *t* on

$H_{ait}$ Number of a/c type *a* inventoried at origin *i* during time *t*

$HP_{akt}$ Number of a/c type *a* inventoried at destination *k* during time *t*

$NPLANES_{at}$ Number of a/c type *a* in the airlift system during time *t*

$TONSUE_{gart}$ Stons of group *g* UE sent on a/c type *a* along route *r* with start time *t*

$TPAX_{gart}$ Group *g* PAX sent on a/c type *a* along route *r* with start time *t*

$BLKNOGO_u$ Stons of bulk-sized UE from unit *u* not sent within the delivery window

$OVRNOGO_u$ Stons of over-sized UE from unit *u* not sent within the delivery window

$OUTNOGO_u$ Stons of out-sized UE from unit *u* not sent within the delivery window

$BLKONOVR_u$ Stons of unit *u* bulk-sized cargo sent on aircraft capable of carrying up to over-sized cargo

$BLKONOUT_u$ Stons of unit *u* bulk-sized cargo sent on aircraft capable of carrying up to out-sized cargo

$OVRONOUT_u$ Stons of unit *u* over-sized cargo sent on aircraft capable of carrying up to out-sized cargo

$PAXNOGO_u$ Unit *u* PAX not sent within the delivery window

### 5. Objective Function

The primary component in the objective function of the model is to minimize the sum of the penalties for undelivered PAX and UE. These penalties are the product of a unit-specific weight and the amount of cargo or troops not sent. The secondary component of the objective function, as discussed in Morton, Rosenthal, and Lim (1995), has much less weight than the primary component; it rewards release of those aircraft no longer required for deliveries. The objective function is:

**Minimize**

$$\sum_{u}(NoGoPenPax_u * PAXNOGO_u + NoGoPenUE_u * UENOGO_u) \quad +$$

$$\sum_{a}\sum_{t} Preserve_{at} * NPLANES_{at}$$

Because aggregation has eliminated the ability to distinguish deliveries among units within groups, this objective function no longer has a penalty for late deliveries. The length of the delivery window has not been reduced, however. In order to ensure as much UE/PAX are delivered on time as possible, the disaggregation model's objective function will include a lateness penalty, while allowing delivery in the same window as the aggregation model.

## 6. Constraints

### a. Demand Satisfaction

The Unit Aggregation Model has four sets of demand satisfaction constraints. The first three ensure delivery of cargo over each of the cargo classes. These constraints ensure cargo compatibility and account for cargo shipped by aircraft capable of carrying larger sized cargo.

$$\sum_{a \in bulk} \sum_{r \in R_{au}} \sum_{t \in RT_{uar}} TONSUE_{gart} + \sum_{u' \in RPR_{gu}} (BLKNOGO_{u'} + BLKONOVR_{u'} + BLKONOUT_{u'}) \geq \sum_{u' \in RPR_{gu}} ProBulk_{u'} * MoveUE_{u'} \qquad , \forall g, u \in U_g$$

$$\sum_{a \in ovr} \sum_{r \in R_{au}} \sum_{t \in RT_{uar}} TONSUE_{gart} + \sum_{u' \in RPR_{gu}} (OVRNOGO_{u'} + OVRONOUT_{u'} - BLKONOVR_{u'}) \geq \sum_{u' \in RPR_{gu}} ProOvr_{u'} * MoveUE_{u'} \qquad , \forall g, u \in U_g$$

$$\sum_{a \in out} \sum_{r \in R_{au}} \sum_{t \in RT_{uar}} TONSUE_{gart} + \sum_{u' \in RPR_{gu}} (OUTNOGO_{u'} - BLKONOUT_{u'} - OVRONOUT_{u'}) \geq \sum_{u' \in RPR_{gu}} ProOut_{u'} * MoveUE_{u'} \qquad , \forall g, u \in U_g$$

These three constraints differ from their THRUPUT2 counterparts in that they account for the type of aircraft on which differing classes of cargo are shipped. They also differentiate cargo not sent by its class. These modifications were necessary to allow construction of the maximum delivery constraints,and, incidentally, add some resolution desired by AFSAA.

The fourth demand constraint ensures the delivery of passengers.

$$\sum_{a}\sum_{r\in R_{au}}\sum_{t\in RT_{uar}} TPAX_{gart} + \sum_{u'\in RPR_{gu}} PAXNOGO_{u} \geq \sum_{u'\in RPR_{gu}} MovePax_{u} \qquad ,\forall g,u\in U_{g}$$

This constraint is basically the same as the corresponding constraint for THRUPUT2.

#### b. Maximum Delivery

These constraints allow delivery of only UE and PAX which are available for loading at the time period in question. In so doing, they prevent delivery after a unit's RDD (including the extension) or before the unit's ALD. There will be one constraint for each unique ALD in a group, less one for the first ALD. Thus, there will be no maximum delivery constraints written for those groups which have only one unit.

$$\sum_{a\in bulk}\sum_{r\in R_{au}}\sum_{t\in AT_{u}} TONSUE_{gart} + \sum_{u'\in APA_{gu}}(BLKNOGO_{u'} + BLKONOVR_{u'} + BLKONOUT_{u'})$$
$$\leq \sum_{u'\in APA_{gu}} PROBlk_{u'} * MoveUE_{u'} \qquad ,\forall g,u\in U_{g},u\neq First_{g}$$

$$\sum_{a\in ovr}\sum_{r\in R_{au}}\sum_{t\in AT_{u}} TONSUE_{gart} + \sum_{u'\in APA_{gu}}(OVRNOGO_{u'} + OVRONOUT_{u'} - BLKONOVR_{u'})$$
$$\leq \sum_{u'\in APA_{gu}} ProOvr_{u'} * MoveUE_{u'} \qquad ,\forall g,u\in U_{g},u\neq First_{g}$$

$$\sum_{a\in out}\sum_{r\in R_{au}}\sum_{t\in AT_{u}} TONSUE_{gart} + \sum_{u'\in APA_{gu}}(OUTNOGO_{u'} - BLKONOUT_{u'} - OVRONOUT_{u'})$$
$$\leq \sum_{u'\in APA_{gu}} ProOut_{u'} * MoveUE_{u'} \qquad ,\forall g,u\in U_{g},u\neq First_{g}$$

$$\sum_{a}\sum_{r\in R_{au}}\sum_{t\in AT_{u}} TPAX_{gart} + \sum_{u'\in APA_{gu}} PAXNOGO_{u'} \leq \sum_{u'\in APA_{gu}} MovePax_{u'} \quad ,\forall g,u\in U_{g},u\neq First_{g}$$

The nondelivery variables (e.g., $BLKNOGO_u$) and the variables allowing shipment of cargo on aircraft capable of handling larger cargo (e.g., $OVRONOUT_u$) are necessary to account for cargo by class and delivery aircraft type. If undelivered cargo is not segregated by class, infeasibilities will occur when the total amount of undelivered cargo is greater than the amount of, say, over-sized cargo to be delivered. Further, because it is necessary to account for all deliveries of a certain cargo class in one constraint, variables which permit out of class cargo-to-aircraft matchings are necessary.

### *c. A/C Balance*

The following five sets of constraints ensure that all aircraft are accounted for and that no more aircraft are used than are in the mobility system at any given time. The first two balance the flow of aircraft at origin and destination airfields, respectively.

$$\sum_{g} \sum_{r \in DR_i} X_{gart} + H_{ait} + RELEASE_{ait} = H_{ai,t-1} + ALLOT_{ait} + \sum_{r \in R_{ai}} \sum_{t'+[CTime_{ar}]=t} Y_{art'} \qquad ,\forall a,i,t$$

$$\sum_{r \in RR_k} Y_{art} + HP_{akt} = HP_{ak,t-1} + \sum_{g} \sum_{r \in R_{ak}} \sum_{\substack{t' \in T_{gar} \\ t'+[CTime_{ar}]=t}} X_{gart'} \qquad ,\forall a,k,t$$

The third constraint limits the quantity of aircraft allocated to origin airfields to the supply of aircraft.

$$\sum_{i} ALLOT_{ait} \le Supply_{at} \qquad ,\forall a,t$$

The fourth ensures that aircraft released from the system are no longer used by the model.

$$NPLANES_{at} = \sum_{t'=1}^{t}\sum_{i} ALLOT_{ait'} - \sum_{t'=1}^{t}\sum_{i} RELEASE_{ait'} \qquad ,\forall a,t$$

The final aircraft conservation constraint set compensates for problems which arise from rounding $CTime_{ar}$. For a more in-depth discussion of the workings of this constraint, see Morton, Rosenthal, and Lim (1995).

$$\sum_{r\in R_a}\sum_{t'=1}^{t} K_{artt'} * (X_{art'} + Y_{art'}) + \sum_{i}\sum_{t'=1}^{t} H_{ait'} + \sum_{k}\sum_{t'=1}^{t} HP_{akt'} \le \sum_{t'=1}^{t} NPLANES_{at'} \qquad ,\forall a,t$$

where

$$K_{artt'} = \begin{cases} t - t' + 1 & \text{if } t' \le t < t' + CTime_{ar} - 1 \\ CTime_{ar} & \text{if } t > t' + CTime_{ar} - 1 \end{cases}$$

Except for a change in indices from units to groups, all aircraft balance constraints are identical to their THRUPUT2 counterparts.

#### d. *Troop Carriage*

This constraint set limits the amount of passengers being carried to the number of seats available on the aircraft.

$$TPAX_{gart} \le MaxPax_a * X_{gart} \qquad ,\forall g,a,r,t{:}t \in T_{gar}$$

#### e. *Maximum Payload*

Here, we limit the total payload of aircraft to the weight allowable along the given route.

$$TONSUE_{gart} + PaxWt * TPAX_{gart} \le MaxLoad_{ar} * X_{gart} \qquad ,\forall g,a,r,t{:}t \in T_{gar}$$

### *f. Floor Space*

We also limit the amount of floor space for PAX and UE to the total available footage for the aircraft.

$$PaxSqFt_a * TPAX_{gart} + WtdAvgUESqFt_{gt} * TONSUE_{gart} \le LoadEff_a * X_{gart} \qquad ,\forall g,a,r,t$$

### *g. A/C Utilization*

The total flying hours consumed by the aircraft are limited to a quantity established by the Air Mobility Command.

$$\sum_g \sum_{r \in R_a} \sum_{t \in T_{gar}} FltTime_{ar} * X_{gart} + \sum_{r \in R_a} \sum_t FltTime_{ar} * Y_{art} \le \sum_t URate_a * NPLANES_{at} \qquad ,\forall a$$

### *h. A/C Handling*

This final set of constraints limits the number of flights in and out of an airfield to the handling capacity of the airfield.

$$\sum_g \sum_a \sum_{r \in R_a} \sum_{\substack{t' \in T_{gar} \\ t' + [Dtime_{abr}] = t}} (MOGReq_{ab} * GTime_{abr}) * X_{gart'}$$

$$+ \sum_a \sum_{r \in R_a} \sum_{\substack{t' \in T_{gar} \\ t' + [Dtime_{abr}] = t}} (MOGReq_{ab} * GTime_{abr}) * Y_{art'} \le MOGEff_{bt} * MOGCap_{bt} \qquad ,\forall b,t$$

## D. IMPACT OF REFORMULATION

Although the Unit Aggregation Model is based on the THRUPUT2 model, several major differences exist between the two. We have aggregated cargo densities for units within groups. Additionally, we have removed some constraints and variables while adding others.

Flight variables (X), and troop and cargo delivery variables (TONSUE and TPAX) are now indexed by groups instead of units. This results in a variable reduction for each instance in which more than one unit was being delivered over the same $(i,k)$ combination during the same time period. However, we have added six variables for each unit while removing one. This addition to the total number of variables is small compared to the reduction allowed when X, TONSUE, and TPAX are indexed by groups instead of units.

We have added four maximum delivery constraints for each unique ALD for units within a group, less one for the first unit to begin delivery in the group. However, this increase is offset by a significant reduction in the number of aircraft capacity constraints, which are now indexed over groups rather than units. This savings is large because aircraft capacity constraints are also indexed over aircraft types, routes, and time periods.

The aggregation of units into groups has reduced the size of one index set. While additional constraints and variables were required for the reformulation, the reduction in the size of the model is quite significant. For a discussion of this reduction, see the model size comparison in Chapter IV. However, the solution to this model is difficult to interpret when unit resolution is desired. Therefore, we develop a secondary model which disaggregates groups into units.

# III. DISAGGREGATION MODEL

In the Unit Aggregation Model, we sacrificed some unit resolution and, thereby, the ability to discern lateness. This chapter develops a small secondary optimization model that takes the Unit Aggregation Model's solution as input and attempts to remedy this shortcoming. This model solves quickly relative to the Unit Aggregation Model. Optimization is necessary here because a new loading assignment of units onto previously scheduled aircraft must be determined. Because we require another optimization model and once again have unit-level resolution, we have reinstated the late delivery penalty in the objective function.

## A. WORD FORMULATION

This model assigns UE and PAX from each unit to flights scheduled by the Unit Aggregation Model subject to the handling capacities of the aircraft. We require four sets of demand satisfaction constraints similar to those in the previous model. We also have three sets of aircraft capacity constraints.

## B. MATHEMATICAL FORMULATION

### 1. Additional Model Information

All indices, sets, and data remain the same with the following exceptions:

**a. *Index Sets***

$T'_{uar}$ The set of all days in which UE and PAX from unit *u* can be sent on a/c type *a*, over route *r*, and arrive by the unit's required delivery date

**b. *Data***

$\bar{X}_{gart}$ The optimal value of the $X_{gart}$ variable in the unit aggregation model

$DaysLate_{uart}$ The number of days late UE and/or PAX from unit *u* would be if it left on a/c type *a* in time *t* and flew along route *r*

$LatePenUE_u$ The penalty for each day of lateness for UE from unit *u*

$LatePenPAX_u$ The penalty for each day of lateness for PAX from unit *u*

$MaxLate_u$ The maximum allowed number of days late a unit *u* delivery is allowed

**c. *Variables***

For the disaggregation model, we will use the same delivery and non-delivery variables as in the Unit Aggregation Model with one exception. The TONSUE and TPAX are now indexed over units instead of groups. We use primes to designate this difference.

## 2. Objective Function

We will use an objective function which minimizes non-delivery and late delivery penalties.

***Minimize***

$$\sum_{u}\sum_{a}\sum_{r\in R_a}\sum_{t\in T'_{uar}} LatePenUE_u * DaysLate_{uart} * TONSUE'_{uart} \quad +$$

$$\sum_{u}\sum_{a}\sum_{r\in R_a}\sum_{t\in T'_{uar}} LatePenPAX_u * DaysLate_{uart} * TPAX'_{uart} \quad +$$

$$\sum_{u}(NoGoPenUE_u * UENOGO'_u + NoGoPenPAX_u * PAXNOGO'_u)$$

## 3. Constraints

### a. *Demand Satisfaction*

The four following sets of constraints ensure demand satisfaction for UE and PAX from unit *u*. There are four sets; one for each type of cargo and troops.

$$\sum_{a\in A_{bulk}}\sum_{r\in R_{au}}\sum_{t\in T_{uar}} TONSUE'_{uart} + UENOGO'_u = MoveUE_u \qquad \forall u\text{: } MoveUE_u > 0$$

$$\sum_{a\in A_{out}}\sum_{r\in R_{au}}\sum_{t\in T_{uar}} TONSUE'_{uart} + UENOGO'_u \geq ProOut_u * MoveUE_u \qquad \forall u\text{: } MoveUE_u > 0$$

$$\sum_{a\in A_{over}}\sum_{r\in R_{au}}\sum_{t\in T_{uar}} TONSUE'_{uart} + UENOGO'_u \geq (ProOut_u + ProOver_u) * MoveUE_u$$

$$\forall u\text{: } MoveUE_u > 0$$

$$\sum_{a}\sum_{r\in R_{au}}\sum_{t\in T_{uar}} TPAX'_{uart} + PAXNOGO'_u = MovePAX_u \qquad \forall u\text{: } MovePAX_u > 0$$

### b. *Aircraft Capacity*

The following constraints ensure that the capacity of the aircraft is not exceeded by the assigned payload.

$$\sum_{u \in U_g} TPAX'_{uart} \leq MaxPAX_a * \bar{X}_{gart} \qquad \forall g,a,r,t:t \in T_{gar}$$

$$\sum_{u \in U_g} TONSUE'_{uart} + PAXWt * TPAX'_{uart} \leq MaxLoad_{ar} * \bar{X}_{gart} \qquad \forall g,a,r,t:t \in T_{gar}$$

$$\sum_{u \in U_g} (PAXSqFt_a * TPAX'_{uart} + UESqFt_u * TONSUE'_{uart}) \leq ACSqFt_a * LoadEff_a * \bar{X}_{gart}$$

$$\forall g,a,r,t:t \in T_{gar}$$

Because the formulation for the disaggregation model merely limits cargo and troops sent to the capacities of the aircraft scheduled by the aggregation model, it will always provide a feasible solution. However, the combination of the two models may yield a suboptimal result. This possibility lies in the use of the weighted densities. Because the weighted density is the same for any unit delivering in a given time period, those units with much higher densities will effectively have their density reduced. This reduction in density may allow the model to deliver more cargo for that unit than it should. The disaggregation model will prevent this excess delivery from taking place. However, this may now give us an unused airlift capacity for the time period. This excess capacity could potentially have been used somewhere else in the model, thus producing a suboptimal solution.

The disaggregation model will solve very quickly because it merely assigns UE and PAX to aircraft missions scheduled by the Unit Aggregation Model. It therefore has no concerns other than demand satisfaction and aircraft

capacity. For additional speed, if needed, the model could be solved as a series of smaller models, one for each group.

While some degree of optimality is sacrificed when using the aggregation/disaggregation model combination, the reduction in model size could become a critical factor in whether or not a model can be solved. The disaggregation model provides the same unit resolution as THRUPUT2, including optimizing delivery for timeliness.

# IV. PERFORMANCE AND COMPARISON

## A. PERFORMANCE OF UNIT AGGREGATION/DISAGGREGATION MODEL COMBINATION

For comparison to THRUPUT2, we used the same notional data set used by Lim (described in his thesis). Using GAMS/OSL and an RS6000/590 computer, the unit aggregation/ disaggregation model combination took just over 100 seconds to generate and solve the scenario. Solving the same scenario with the same computer and software, THRUPUT2 takes about 43% more time.

## B. COMPARISON WITH THRUPUT2

Here we compare model size, time requirements, and delivery performance. There are two different data sets used in this comparison. The first is a small, notional data set; the other is larger and based on actual data for a two MRC scenario.

### 1. Model Size

In Table 1, we see the size differences between the Unit Aggregation Model and THRUPUT2. Table I compares the two models for both the notional data set and the two MRC data set. When solving large models, the largest

| | Notional Data Set | | Two MRC Data Set | |
|---|---|---|---|---|
| | Unit Aggregation | THRUPUT2 | Unit Aggregation | THRUPUT2 |
| rows | 5,793 | 7,485 | 26,790 | 198,237 |
| columns | 9,389 | 11,093 | 33,175 | 210,727 |
| nonzeroes | 43,017 | 55,174 | 189,231 | 1,217,745 |

Table 1. A comparison of model size and nonzero quantities for the two models using both data sets.

consumption of memory is due to the number of nonzeroes in

the model. Examining the figures for the notional data set, the quantity of nonzeroes in the unit aggregation model is about 80% of those in THRUPUT2; for the two MRC Data Set, the quantity of nonzeroes is about 15%. The difference in memory savings for the two data sets is actually quite dramatic (20% for the notional data set versus over 80% for the more realistic scenario). The explanation for this difference is in the nature of the data sets. The notional data set has nine different $(i,k)$ pairs for twenty units. The more realistic data set has over 220 units and 23 different origin/desination pairs.

### 2. Time Requirements

The time savings for each data set is significant. For the notional data set, THRUPUT2 takes about 40 seconds to generate and 100 seconds to solve on the RS6000. The unit aggregation model takes 35 seconds to generate and 65 seconds to solve, and the disaggregation model requires 15 seconds for generation and 20 seconds for solving. For the two MRC scenario, the difference in time to generate and solve is more dramatic. It takes an hour to generate and over two hours to solve using THRUPUT2. The unit aggregation model took six minutes to generate and ten minutes to solve, and the disaggregation model required only one minute for generation and three minutes to arrive at a solution. The time required for generating and solving the scenario is reduced by almost 90%.

### 3. Delivery Results

Figure 2 compares the cumulative delivery results for each model with the cumulative demand for the notional scenario. The cargo delivery profile for each model is quite similar. Large differences in the cargo densities for units in the same groups cause the discrepancy between the two delivery profiles. In the unit aggregation model, these densities were weighted for each group. This weighting caused the group's density to be less than some member units' cargo densities. The difference made it impossible to ship as much UE during a unit's delivery window given the flights scheduled by the unit aggregation model.

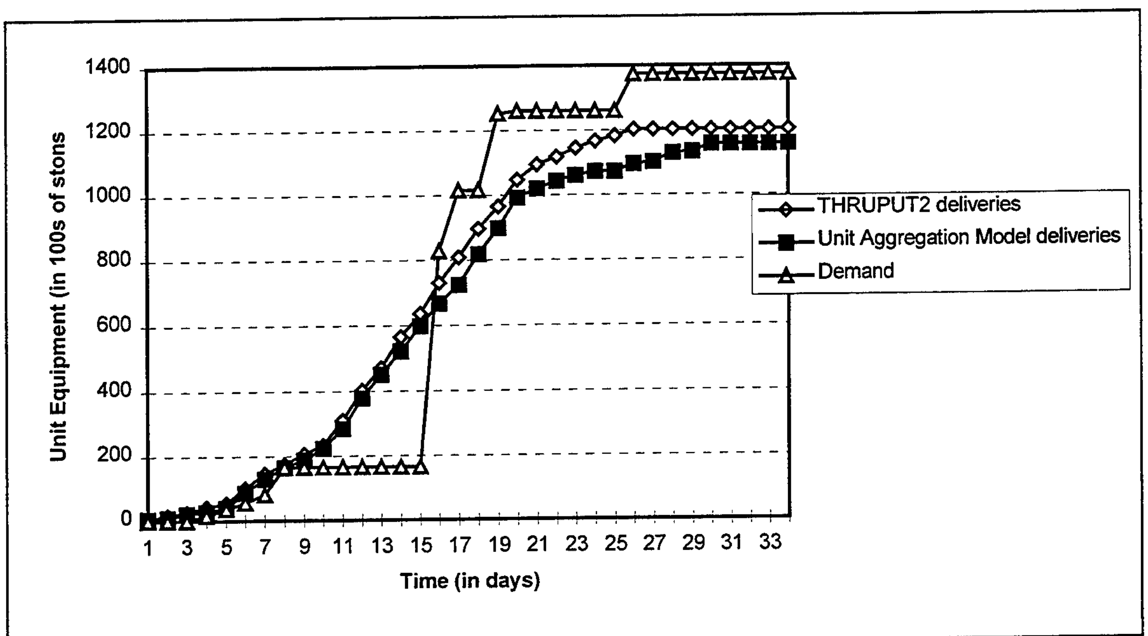


Figure 2. A display of cumulative deliveries of unit equipment for the two models compared to the cumulative demand for the notional scenario. Note the differences in the delivery profiles. This is due to the use of weighted densities for units within groups.

Figure 3 shows the same delivery profiles for the two MRC scenario. Note that the aggregation/disaggregation

model combination allowed more deliveries than THRUPUT2. This delivery profile created by the Unit Aggregation Model is not a feasible solution for THRUPUT2. This difference requires more extensive analysis, but is likely due to the use of cumulative demand satisfaction and maximum delivery constraints.

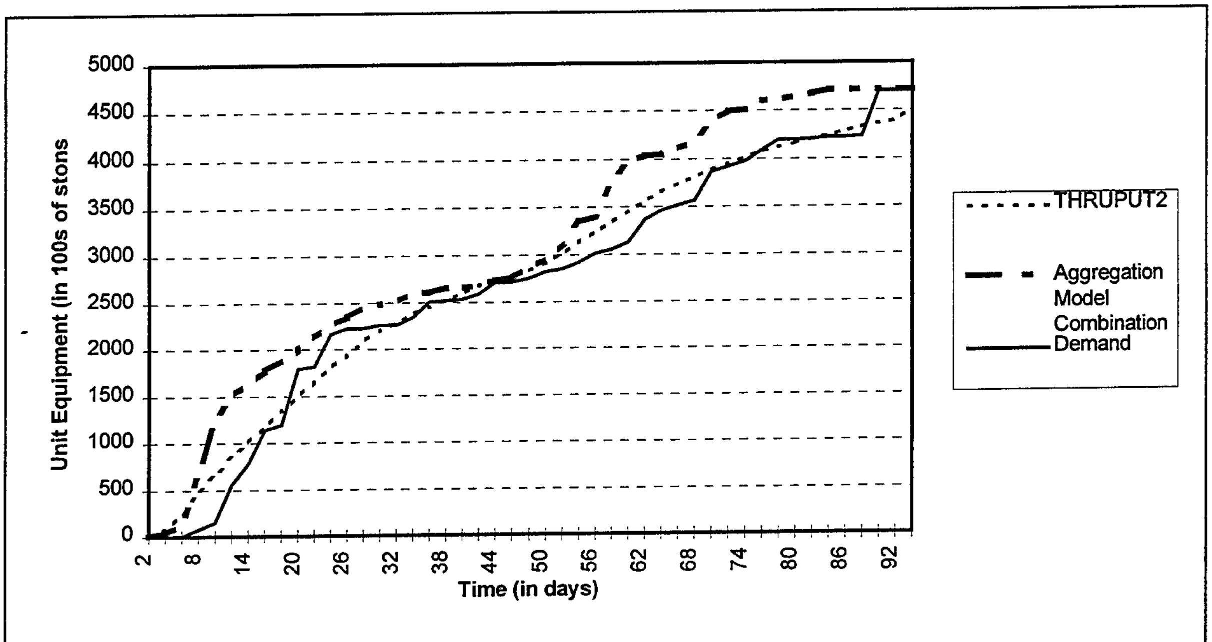


Figure 3. A display of cumulative deliveries of unit equipment for the two models compared to the cumulative demand for the two MRC scenario.

Unit closure is a metric U.S. Air Force uses to make comparisons between model runs. A unit is considered closed when all unit equipment for that unit has been shipped to its destination. The difference in closure for the notional data set is significant. While THRUPUT2 fails to close only two units, the aggregation/disaggregation model combination fails to close ten. However, this metric may be somewhat misleading. Neither model is actually optimizing closure.

It may be possible to close more units in either scenario by shifting cargo loading from one unit to another.

# V. CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

## A. CONCLUSIONS

The Unit Aggregation/Disaggregation Model combination can be used to solve the same scenarios as THRUPUT2. The combination is smaller and takes less time to generate and solve. It also may alleviate the need to aggregate time in order to solve a scenario. In these respects, the combination forms a better model.

In addition to the memory savings, the model also now requires less time to generate and solve. This brings the model back in line with its original intentions of being a "quick turn" model.

## B. LIMITATIONS

When we put units and their associated UE and PAX through the aggregation/disaggregation, we lose the resolution we had in THRUPUT2. For example, as cited earlier in Chapter IV, we may cause problems by aggregating units with significantly different cargo densities. Further, the model combination may allow more deliveries than is feasible for THRUPUT2.

## C. RECOMMENDATIONS

The Unit Aggregation Model can be recommended because of its tremendous savings in time and reduction in model size. With the time savings, we get the flexibility to examine several different scenarios in a much shorter time span. As a result of the size reduction, we might also add

features to the model's capabilities such as aerial refueling or intra-theater cargo delivery. However, use of the Unit Aggregation Model requires some caution. Due to problems noted in previous sections, we should only aggregate units with similar densities. This will increase the time and size to some degree, but will still form a leaner, faster model than THRUPUT2.

# APPENDIX A. MATHEMATICAL FORMULATION OF THRUPUT2

The following mathematical formulation of THRUPUT2 is excerpted from Morton, Rosenthal, and Lim [1995].

### Indices

| | |
|---|---|
| $u$ | indexes units, e.g., 82nd Airborne |
| $a$ | indexes aircraft types, e.g., C5, C141 |
| $t, t'$ | index time periods |
| $b$ | indexes all airfields (origins, enroutes and destinations) |
| $i$ | indexes origin airfields |
| $k$ | indexes destination airfields |
| $r$ | indexes routes |

### Index Sets

*Airfield Index Sets*

| | |
|---|---|
| $B$ | set of available airfields |
| $I \subseteq B$ | origin airfields |
| $K \subseteq B$ | destination airfields |

*Aircraft Index Sets*

| | |
|---|---|
| $A$ | set of available aircraft types |
| $A_{bulk} \subseteq A$ | aircraft capable of hauling bulk-sized cargo |
| $A_{over} \subseteq A_{bulk}$ | aircraft capable of hauling over-sized cargo |
| $A_{out} \subseteq A_{over}$ | aircraft capable of hauling out-sized cargo |

Bulk cargo is palletized on 88 x 108 inch platforms and can fit on any milatary aircraft (as well as the cargo-configured 747). Over-sized cargo is non-palletized rolling stock: it is larger than bulk cargo and can fit on a C141, C5 or C17. Out-sized cargo is very large non-palletized cargo that can fit into a C5 or C17 but not a C141.

*Route Index Sets*

| | |
|---|---|
| $R$ | set of available routes |
| $R_a \subseteq R$ | permissible routes for aircraft type $a$ |
| $R_{ab} \subseteq R_a$ | permissible routes for aircraft type $a$ that use airfield $b$ |
| $R_{aik} \subseteq R_a$ | permissible routes for aircraft type $a$ that have origin $i$ and destination $k$ |
| $DR_i \subseteq R$ | delivery routes that originate from origin $i$ |
| $RR_k \subseteq R$ | recovery routes that originate from destination $k$ |

A *delivery route* is a route flown from a specific unit's origin to its destination for the purpose of delivering cargo and/or passengers. A *recovery route* is a route flown from a unit's destination to that unit's

or some other unit's origin, for the purpose of making another delivery. Since recovery flights carry much less weight than deliveries, the recovery routes from $k$ to $i$ may have fewer enroute stops than the delivery routes from $i$ to $k$.

*Time Index Sets*

| | |
|---|---|
| $T$ | set of time periods |
| $T_{uar} \subseteq T$ | possible launch times of missions for unit $u$ using aircraft type $a$ and route $r$ |

The set $T_{uar}$ covers the allowed time window for unit $u$, which starts on the unit's available-to-load date and ends on the unit's required delivery date, plus some extra time up to the maximum allowed lateness for the unit.

**Given Data**

*Movement Requirements Data*

| | |
|---|---|
| $MovePAX_{uik}$ | Troop movement requirement for unit $u$ from origin $i$ to destination $k$ |
| $MoveUE_{uik}$ | Equipment movement requirement in short tons (stons) for unit $u$ from origin $i$ to destination $k$ |
| $ProBulk_u$ | Proportion of unit $u$ cargo that is bulk-sized |
| $ProOver_u$ | Proportion of unit $u$ cargo that is over-sized |
| $ProOut_u$ | Proportion of unit $u$ cargo that is out-sized |

*Penalty Data*

| | |
|---|---|
| $LatePenUE_u$ | Lateness penalty (per ston per day) for unit $u$ equipment |
| $LatePenPAX_u$ | Lateness penalty (per soldier per day) for unit $u$ troops |
| $NoGoPenUE_u$ | Non-delivery penalty (per ston) for unit $u$ equipment |
| $NoGoPenPAX_u$ | Non-delivery penalty (per soldier) for unit $u$ troops |
| $MaxLate$ | Maximum allowed lateness (in days) for delivery |
| $Preserve_{at}$ | Penalty (small artificial cost) for keeping aircraft type $a$ in mobility system at time $t$ |

*Cargo Data*

| | |
|---|---|
| $UESqFt_u$ | Average cargo floor space (in sq. ft.) per ston of unit *u* equipment |
| $PAXWt_u$ | Average weight of a unit *u* soldier inclusive of personal equipment |

*Aircraft Data*

| | |
|---|---|
| $Supply_{at}$ | Number of aircraft of type *a* that become available at time *t* |
| $MaxPAX_a$ | Maximum troop carriage capacity of aircraft type *a* |
| $PAXSqFt_{ua}$ | Average cargo space (in sq. ft.) consumed by a unit *u* soldier for aircraft type *a* |
| $ACSqFt_a$ | Cargo floor space (in sq. ft.) of aircraft type *a* |
| $LoadEff_a$ | Cargo space loading efficiency (<1) for aircraft type *a*. This accounts for the fact that it is not possible in practice to fully utilize the cargo space. |
| $URate_a$ | Established utilization rate (flying hours per aircraft per day) for aircraft type *a* |

*Airfield Data*

| | |
|---|---|
| $MOGCap_{bt}$ | Aircraft capacity (in narrow-body equivalents) at airfield *b* in time *t* |
| $MOGReq_{ab}$ | Conversion factor to narrow-body equivalents for one aircraft of type *a* at airfield *b* |
| $MOGEff_{bt}$ | MOG efficiency factor (<1), to account for the fact that it is impossible to fully utilize available MOG capacity due to randomness of ground times |

*Aircraft Route Performance Data*

| | |
|---|---|
| $MaxLoad_{ar}$ | Maximum payload (in stons) for aircraft type *a* flying route *r*. |
| $GTime_{abr}$ | Aircraft ground time (due to onload or offload of cargo, refueling, maintenance, etc.) needed for aircraft type *a* at airfield *b* on route *r* |

$DTime_{abr}$ Cumulative time (flight time plus ground time) taken by aircraft type $a$ to reach airfield $b$ along route $r$

$FltTime_{ar}$ Total flying hours consumed by aircraft type $a$ on route $r$

$CTime_{ar}$ Cumulative time (flight time plus ground time) taken by aircraft type $a$ on route $r$

$DaysLate_{uart}$ Number of days late unit $u$'s requirement would be if delivered by aircraft type $a$ via route $r$ with mission start time $t$

**Decision Variables**

*Mission Variables*

$X_{uart}$ Number of aircraft of type $a$ that airlift unit $u$ via route $r$ with mission start time during period $t$

$Y_{art}$ Number of aircraft of type $a$ that recover from a destination airfield via route $r$ with start time during period $t$

*Aircraft Allocation and De-allocation Variables*

$ALLOT_{ait}$ Number of aircraft of type $a$ that are allocated to origin $i$ at time $t$

$RELEASE_{ait}$ Number of aircraft of type $a$ that were allocated to origin $i$ prior to time $t$ but are not scheduled for any missions from time $t$ on

*Aircraft Inventory Variables*

$H_{ait}$ Number of aircraft of type $a$ inventoried at origin $i$ at time $t$

$HP_{akt}$ Number of aircraft of type $a$ inventoried at destination $k$ at time $t$

$NPLANES_{at}$ Number of aircraft of type $a$ in the air mobility system at time $t$

*Airlift Quantity Variables*

$TONSUE_{uart}$ Total stons of unit $u$ equipment airlifted by aircraft of type $a$ via route $r$ with mission start time during period $t$

$TPAX_{uart}$ Total number of unit $u$ troops airlifted by aircraft of type $a$ via route $r$ with mission start time during period $t$

*Elastic (Nondelivery) Variables*

$UENOGO_{uik}$ Total stons of unit $u$ equipment with origin $i$ and destination $k$ that is not delivered in the prescribed time frame

$PAXNOGO_{uik}$ Number of unit $u$ troops with origin $i$ and destination $k$ who are not delivered in the prescribed time frame

**Formulation of the Objective Function**

*Minimize*

$$\sum_{u}\sum_{a}\sum_{r \in R_a}\sum_{t \in T_{uar}} LatePenUE_u * DaysLate_{uart} * TONSUE_{uart}$$

$$+ \sum_{u}\sum_{a}\sum_{r \in R_a}\sum_{t \in T_{uar}} LatePenPAX_u * DaysLate_{uart} * TPAX_{uart}$$

$$+ \sum_{u}\sum_{i}\sum_{k} (NoGoPenUE_u * UENOGO_{uik} + NoGoPenPAX_u * PAXNOGO_{uik})$$

$$+ \sum_{a}\sum_{t} Preserve_{at} * NPLANES_{at}$$

The $DaysLate_{uart}$ penalty parameter has value zero if $t+CTime_{ar}$ is within the prescribed time window for unit $u$. Thus, the first two terms of the objective function take effect only when a delivery is late. The third term in the objective function corresponds to cargo and passengers that cannot be delivered even within the permitted lateness. Late delivery and non-delivery occur only when airlift assets are insufficient for on-time delivery.

**Formulation of the Constraints**

There are five categories of constraints. Their mathematical formulations are as follows.

**Demand Satisfaction Constraints**

These constraints ensure demand satisfaction and account for the desired delivery time-windows by use of the index sets $T_{uar}$ and the lateness parameters $DaysLate_{uart}$.

Demand Satisfaction Constraints for All Classes of Cargo:

$$\sum_{a \in A_{bulk}} \sum_{r \in R_{aik}} \sum_{t \in T_{uar}} TONSUE_{uart} + UENOGO_{uik} = MoveUE_{uik} \quad \forall\ u,i,k:\ MoveUE_{uik} > 0$$

Demand Satisfaction Constraints for Out-Sized Cargo:

$$\sum_{a \in A_{out}} \sum_{r \in R_{aik}} \sum_{t \in T_{uar}} TONSUE_{uart} + UENOGO_{uik} \geq ProOut_u * MoveUE_{uik}$$

$$\forall\ u,i,k:\ MoveUE_{uik} > 0$$

Demand Satisfaction Constraints for Over-Sized Cargo:

$$\sum_{a \in A_{ovr}} \sum_{r \in R_{aik}} \sum_{t \in T_{uar}} TONSUE_{uart} + UENOGO_{uik} \geq (ProOver_u + ProOut_u) * MoveUE_{uik}$$

$$\forall\ u,i,k:\ MoveUE_{uik} > 0$$

Demand Satisfaction Constraints for Troops:

$$\sum_{a} \sum_{r \in R_{aik}} \sum_{t \in T_{uar}} TPAX_{uart} + PAXNOGO_{uik} = MovePAX_{uik} \quad \forall\ u,i,k:\ MovePAX_{uik} > 0$$

**Aircraft Balance Constraints**

Aircraft Balance Constraints at Origin Airfields:

$$\sum_{u} \sum_{r \in DR_i} X_{uart} + H_{ait} + RELEASE_{ait} = H_{ai,t-1} + ALLOT_{ait} + \sum_{r \in R_{ai}} \sum_{t'+[CTime_{ar}]=t} Y_{art'} \qquad \forall a,i,t$$

where $[CTime_{ar}]$ is $CTime_{ar}$ rounded to the nearest integer.

Aircraft Balance Constraints at Destination Airfields:

$$\sum_{r \in RR_k} Y_{art} + HP_{akt} = HP_{ak,t-1} + \sum_{u} \sum_{r \in R_{ak}} \sum_{\substack{t' \in T_{uar} \\ t'+[CTime_{ar}]=t}} X_{uart'} \qquad \forall a,k,t$$

*Aircraft Balance Constraints for Allocations to Origins:*

$$\sum_{t'=1}^{t}\sum_{i} ALLOT_{ait} \le \sum_{t'=1}^{t} Supply_{at} \quad \forall a,t$$

This constraint is in the cumulative form, rather than in the simpler form $S_i Allot_{ait} \le Supply_{at}$, to allow aircraft that become available in period $t$ to be put into service at a later period.

*Aircraft Balance Constraints Accounting for Allocations and Releases:*

$$NPLANES_{at} = \sum_{t'=1}^{t}\sum_{i} ALLOT_{ait'} - \sum_{t'=1}^{t}\sum_{i} RELEASE_{ait'} \qquad \forall a,t$$

*Cumulative Aircraft Balance Constraints:*

$$\sum_{r\in R_a}\sum_{t'=1}^{t}\sum_{u} K_{artt'} * X_{uart'} + \sum_{r\in R_a}\sum_{t'=1}^{t} K_{artt'} + \sum_{i}\sum_{t'=1}^{t} H_{ait'}$$
$$+ \sum_{k}\sum_{t'=1}^{t} HP_{akt'} \le \sum_{t'=1}^{t} NPLANES_{at'}$$

where

$$K_{artt'} = \begin{cases} t - t' + 1 & \text{if } t' \le t < t' + CTime_{ar} - 1 \\ CTime_{ar} & \text{if } t \ge t' + CTime_{ar} - 1 \end{cases}$$

**Aircraft Capacity Constraints**

*Troop Carriage Capacity Constraints:*

$$TPAX_{uart} \le MaxPAX_a * X_{uart} \quad \forall u,a,r,t: t \in T_{uar}$$

*Maximum Payload Constraints:*

$$TONSUE_{uart} + PAXWt * TPAX_{uart} \le MaxLoad_{ar} * X_{uart} \quad \forall u,a,r,t: t \in T_{uar}$$

*Cargo Floor Space Constraints:*

$$PAXSqFt_a * TPAX_{uart} + UESqFt_u * TONSUE_{uart} \le ACSqFt_a * LoadEff_a * X_{uart}$$

$$\forall u,a,r,t: t \in T_{uar}$$

**Aircraft Utilization Constraints**

$$\sum_{u}\sum_{r\in R_a}\sum_{t\in T_{uqr}} FltTime_{ar} * X_{uart} + \sum_{r\in R_a}\sum_{t} FltTime_{ar} * Y_{art}$$

$$\leq \sum_{t} URate_a * NPlanes_{at} \quad \forall a$$

**Aircraft Handling Capacity of Airfields (MOG Constraint)**

$$\sum_{u}\sum_{a}\sum_{r\in R_a}\sum_{\substack{t'\in T_{uar} \\ t'+[DTime_{abr}]=t}} (MOGReq_{ab} * GTime_{abr} / 24) * X_{uart'}$$

$$+ \sum_{a}\sum_{r\in R_a}\sum_{\substack{t'\in T_{uar} \\ t'+[DTime_{abr}]=t}} (MOGReq_{ab} * GTime_{abr} / 24) * Y_{art'}$$

$$\leq \quad MOGEff_{bt} * MOGCap_{bt} \qquad \forall b,t$$

# APPENDIX B. RESULTS FOR NOTIONAL DATA SET

1. Results from Unit Aggregation/Disaggregation Model combination.

| | CLOSE DATE | ALD | RDD | ON TIME | LATE DELIVER | NO GO | TOTAL |
|---|---|---|---|---|---|---|---|
| UNITA | 20.12 | 8.00 | 17.00 | 81.07 | 105.70 | | 86.77 |
| UNITB | 22.32 | 16.00 | 20.00 | 6.92 | | | 6.92 |
| UNITC | NA | 3.00 | 8.00 | 3.79 | 36.80 | 22.64 | 63.23 |
| UNITD | NA | 21.00 | 26.00 | 39.20 | 61.19 | 14.55 | 114.94 |
| UNITE | NA | 3.00 | 16.00 | 140.33 | 66.44 | 125.07 | 331.85 |
| UNITE2 | NA | 3.00 | 16.00 | 236.58 | 87.85 | 7.41 | 331.84 |
| UNITF | NA | 11.00 | 19.00 | 158.90 | 72.12 | 7.24 | 238.27 |
| UNITG | 1.53 | 1.00 | 4.00 | 5.03 | | | 5.03 |
| UNITH | NA | 1.00 | 4.00 | | | 10.13 | 10.13 |
| UNITI | 3.40 | 2.00 | 5.00 | 5.03 | | | 5.03 |
| UNITJ | NA | 2.00 | 5.00 | | | 10.13 | 10.13 |
| UNITK | 6.39 | 2.00 | 5.00 | 3.10 | 1.93 | | 5.03 |
| UNITL | 9.39 | 2.00 | 6.00 | 1.68 | 3.23 | | 4.91 |
| UNITM | 8.39 | 3.00 | 6.00 | 3.83 | 1.39 | | 5.22 |
| UNITN | 10.39 | 3.00 | 6.00 | 1.93 | 3.10 | | 5.03 |
| UNITO | NA | 3.00 | 6.00 | 4.91 | | | 4.91 |
| UNITP | NA | 3.00 | 7.00 | | | 5.22 | 5.22 |
| UNITQ | 7.83 | 4.00 | 7.00 | 10.13 | | | 10.13 |
| UNITR | 7.84 | 4.00 | 7.00 | 10.13 | | | 10.13 |
| UNITS | 8.84 | 4.00 | 8.00 | 10.13 | | | 10.13 |
| UNITT | NA | 4.00 | 8.00 | | | 10.13 | 10.13 |
| TOTAL | | | | 710.86 | 446.68 | 217.43 | 1374.98 |

2. Results from THRUPUT2.

| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | NO GO | TOTAL |
|---|---|---|---|---|---|---|---|
| UNITA | 21.12 | 8.00 | 17.00 | 142.55 | 44.22 | | 186.77 |
| UNITB | 21.32 | 16.00 | 20.00 | | 6.92 | | 6.92 |
| UNITC | NA | 3.00 | 8.00 | 18.70 | 28.07 | 16.46 | 63.23 |
| UNITD | 26.84 | 21.00 | 26.00 | 114.94 | | | 114.94 |
| UNITE | NA | 3.00 | 16.00 | 155.04 | 20.51 | 156.30 | 331.84 |
| UNITE2 | 20.53 | 3.00 | 16.00 | 191.84 | 140.00 | | 331.85 |
| UNITF | 22.83 | 11.00 | 19.00 | 188.80 | 49.47 | | 238.27 |
| UNITG | 2.32 | 1.00 | 4.00 | 5.03 | | | 5.03 |
| UNITH | 2.12 | 1.00 | 4.00 | 10.13 | | | 10.13 |
| UNITI | 5.40 | 2.00 | 5.00 | 5.03 | | | 5.03 |
| UNITJ | 7.06 | 2.00 | 5.00 | 8.71 | 1.42 | | 10.13 |
| UNITK | 5.37 | 2.00 | 5.00 | 5.03 | | | 5.03 |
| UNITL | 6.39 | 2.00 | 6.00 | 4.91 | | | 4.91 |
| UNITM | 6.37 | 3.00 | 6.00 | 5.22 | | | 5.22 |
| UNITN | 6.39 | 3.00 | 6.00 | 5.03 | | | 5.03 |
| UNITO | 6.35 | 3.00 | 6.00 | 4.91 | | | 4.91 |
| UNITP | 11.39 | 3.00 | 7.00 | 2.60 | 2.62 | | 5.22 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| UNITQ | 7.84 | 4.00 | 7.00 | 10.13 | | | 10.13 |
| UNITR | 7.84 | 4.00 | 7.00 | 10.13 | | | 10.13 |
| UNITS | 8.83 | 4.00 | 8.00 | 10.13 | | | 10.13 |
| UNITT | 10.06 | 4.00 | 8.00 | 5.24 | 4.89 | | 10.13 |
| TOTAL | | | | 904.10 | 298.12 | 172.76 | 1374.98 |

# APPENDIX C. RESULTS FOR THE TWO MRC DATA SET

1. Results using the aggregation/disaggregation model combination.

| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | TOTAL |
|---|---|---|---|---|---|---|
| 0199 | 2.51 | | 2.00 | 2.06 | | 2.06 |
| 0204 | 4.57 | 4.00 | 4.00 | 0.12 | | 0.12 |
| 0205 | 4.45 | 4.00 | 4.00 | 0.12 | | 0.12 |
| 0206 | 4.47 | 4.00 | 4.00 | 0.12 | | 0.12 |
| 0221 | 2.42 | 2.00 | 8.00 | 2.18 | | 2.18 |
| 0223 | 2.40 | 2.00 | 8.00 | 0.29 | | 0.29 |
| 0237 | 6.13 | 4.00 | 8.00 | 5.67 | | 5.67 |
| 0239 | 6.51 | 4.00 | 8.00 | 50.19 | 1.91 | 52.10 |
| 0256 | 8.54 | 4.00 | 8.00 | 0.35 | | 0.35 |
| 0260 | 8.32 | 4.00 | 8.00 | 0.44 | | 0.44 |
| 0262 | 6.66 | 4.00 | 8.00 | 0.49 | | 0.49 |
| 0264 | 8.13 | 4.00 | 8.00 | 0.18 | | 0.18 |
| 0276 | 8.41 | 6.00 | 8.00 | 0.29 | | 0.29 |
| 0278 | 6.70 | 4.00 | 8.00 | 4.78 | | 4.78 |
| 0293 | 8.51 | 6.00 | 8.00 | 1.17 | | 1.17 |
| 0332 | 8.78 | 8.00 | 8.00 | 0.19 | | 0.19 |
| 0341 | 8.41 | 4.00 | 8.00 | 3.15 | | 3.15 |
| 0353 | 10.71 | 6.00 | 10.00 | 55.25 | | 55.25 |
| 0368 | 22.47 | 22.00 | 22.00 | 11.74 | | 11.74 |
| 0450 | 8.42 | 6.00 | 10.00 | 17.18 | | 17.18 |
| 0459 | 8.78 | 8.00 | 10.00 | 3.44 | | 3.44 |
| 0465 | 6.13 | 4.00 | 10.00 | 4.49 | | 4.49 |
| 0467 | 8.13 | 8.00 | 10.00 | 0.43 | | 0.43 |
| 0536 | 16.55 | 6.00 | 12.00 | 34.73 | 8.15 | 42.88 |
| 0571 | 8.13 | 8.00 | 12.00 | 3.04 | | 3.04 |
| 0573 | 12.08 | 8.00 | 12.00 | 4.00 | | 4.00 |
| 0575 | 8.11 | 8.00 | 12.00 | 2.46 | | 2.46 |
| 0576 | 6.45 | 4.00 | 12.00 | 11.38 | | 11.38 |
| 0580 | 10.57 | 6.00 | 12.00 | 7.01 | | 7.01 |
| 0581 | 6.13 | 6.00 | 12.00 | 6.24 | | 6.24 |
| 0651 | 12.64 | 8.00 | 12.00 | 6.17 | | 6.17 |
| 0655 | 8.47 | 6.00 | 12.00 | 25.53 | | 25.53 |
| 0658 | 12.60 | 8.00 | 12.00 | 290.97 | | 290.97 |
| 0761 | 12.40 | 8.00 | 14.00 | 2.74 | | 2.74 |
| 0796 | 10.66 | 8.00 | 14.00 | 145.05 | | 145.05 |
| 0799 | 10.78 | 10.00 | 14.00 | 12.45 | | 12.45 |
| 0887 | 12.47 | 8.00 | 14.00 | 37.19 | | 37.19 |
| 0888 | 8.54 | 8.00 | 14.00 | 9.10 | | 9.10 |
| 0907 | 8.13 | 8.00 | 14.00 | 2.31 | | 2.31 |
| 0910 | 8.08 | 8.00 | 14.00 | 0.40 | | 0.40 |
| 0940 | 8.63 | 8.00 | 14.00 | 14.61 | | 14.61 |
| 0944 | 14.35 | 8.00 | 16.00 | 0.04 | | 0.04 |
| 0953 | 12.47 | 8.00 | 16.00 | 57.03 | | 57.03 |
| 0954 | 8.57 | 8.00 | 16.00 | 11.75 | | 11.75 |
| 0984 | 20.45 | 8.00 | 16.00 | 15.57 | 6.58 | 22.15 |
| 1030 | 12.08 | 8.00 | 16.00 | 3.86 | | 3.86 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1032 | 16.13 | 8.00 | 16.00 | 1.92 | | 1.92 |
| 1079 | 16.63 | 8.00 | 16.00 | 263.48 | | 263.48 |
| 1085 | 12.55 | 8.00 | 16.00 | 3.99 | | 3.99 |
| 1173 | 18.13 | 6.00 | 18.00 | 21.34 | | 21.34 |
| 1195 | 14.67 | 8.00 | 18.00 | 1.11 | | 1.11 |
| 1206 | 10.78 | 8.00 | 18.00 | 15.83 | | 15.83 |
| 1210 | 8.51 | 8.00 | 18.00 | 10.24 | | 10.24 |
| 1268 | 14.63 | 8.00 | 20.00 | 0.30 | | 0.30 |
| 1271 | 16.26 | 8.00 | 20.00 | 9.18 | | 9.18 |
| 1273 | 12.60 | 8.00 | 20.00 | 17.74 | | 17.74 |

| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | TOTAL |
|---|---|---|---|---|---|---|
| 1290 | 12.54 | 8.00 | 20.00 | 15.62 | | 15.62 |
| 1302 | 12.35 | 10.00 | 20.00 | 0.50 | | 0.50 |
| 1312 | 12.41 | 8.00 | 20.00 | 46.30 | | 46.30 |
| 1318 | 20.60 | 10.00 | 20.00 | 4.63 | | 4.63 |
| 1336 | 8.60 | 8.00 | 20.00 | 13.17 | | 13.17 |
| 1349 | 16.13 | 16.00 | 20.00 | 3.46 | | 3.46 |
| 1495 | 24.60 | 8.00 | 20.00 | 268.58 | 174.27 | 442.85 |
| 1497 | 22.45 | 10.00 | 20.00 | 46.95 | 2.59 | 49.54 |
| 1508 | 26.43 | 14.00 | 22.00 | 0.22 | 0.81 | 1.03 |
| 1519 | 20.13 | 4.00 | 22.00 | 0.55 | | 0.55 |
| 1564 | 26.45 | 12.00 | 22.00 | 11.99 | 2.07 | 14.06 |
| 1619 | 8.60 | 8.00 | 24.00 | 4.80 | | 4.80 |
| 1658 | 12.64 | 8.00 | 24.00 | 19.48 | | 19.48 |
| 1670 | 10.64 | 8.00 | 24.00 | 67.03 | | 67.03 |
| 1692 | 18.50 | 10.00 | 24.00 | 12.16 | | 12.16 |
| 1721 | 14.64 | 10.00 | 24.00 | 0.30 | | 0.30 |
| 1756 | 12.60 | 10.00 | 24.00 | 16.35 | | 16.35 |
| 1800 | 10.57 | 8.00 | 24.00 | 48.59 | | 48.59 |
| 1842 | 8.47 | 8.00 | 24.00 | 5.76 | | 5.76 |
| 1907 | 28.60 | 12.00 | 24.00 | 50.19 | 110.42 | 160.61 |
| 1908 | 22.45 | 12.00 | 24.00 | 14.10 | | 14.10 |
| 1909 | 30.53 | 8.00 | 26.00 | | 15.34 | 15.34 |
| 1941 | 4.13 | 4.00 | 26.00 | 0.49 | | 0.49 |
| 1943 | 14.47 | 8.00 | 26.00 | 43.57 | | 43.57 |
| 2024 | 10.55 | 8.00 | 30.00 | 0.57 | | 0.57 |
| 2032 | 20.50 | 16.00 | 30.00 | 2.09 | | 2.09 |
| 2069 | 28.63 | 20.00 | 30.00 | 27.94 | | 27.94 |
| 2130 | 8.11 | 4.00 | 34.00 | 0.21 | | 0.21 |
| 2135 | 32.47 | 10.00 | 34.00 | 2.55 | | 2.55 |
| 2154 | 8.72 | 8.00 | 34.00 | 75.92 | | 75.92 |
| 2158 | 26.41 | 16.00 | 34.00 | 4.74 | | 4.74 |
| 2184 | 34.08 | 26.00 | 34.00 | 0.37 | | 0.37 |
| 2190 | 26.43 | 20.00 | 34.00 | 2.26 | | 2.26 |
| 2201 | 32.42 | 8.00 | 36.00 | 1.74 | | 1.74 |
| 2259 | 38.43 | 16.00 | 36.00 | 126.73 | 1.86 | 128.59 |
| 2267 | 40.57 | 24.00 | 36.00 | 24.18 | 4.42 | 28.60 |
| 2268 | 34.08 | 28.00 | 36.00 | 0.37 | | 0.37 |
| 2339 | 38.57 | 14.00 | 38.00 | 4.38 | | 4.38 |
| 2342 | 30.63 | 28.00 | 38.00 | 13.83 | | 13.83 |
| 2354 | 12.42 | 10.00 | 40.00 | 0.48 | | 0.48 |
| 2355 | 26.43 | 24.00 | 40.00 | 1.25 | | 1.25 |
| 2361 | 26.42 | 8.00 | 40.00 | 9.64 | | 9.64 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2390 | 10.70 | 8.00 | 42.00 | 34.27 | | 34.27 |
| 2409 | 16.55 | 8.00 | 42.00 | 17.38 | | 17.38 |
| 2423 | 42.50 | 36.00 | 42.00 | 0.27 | | 0.27 |
| 2484 | 48.51 | 18.00 | 44.00 | 108.50 | 13.98 | 122.48 |
| 2565 | 10.78 | 10.00 | 48.00 | 7.17 | | 7.17 |
| 2625 | 48.53 | 44.00 | 48.00 | 3.96 | | 3.96 |
| 2628 | 44.24 | 44.00 | 48.00 | 0.81 | | 0.81 |
| 2637 | 16.35 | 8.00 | 48.00 | 0.54 | | 0.54 |
| 2658 | 24.55 | 14.00 | 48.00 | 1.02 | | 1.02 |
| 2661 | 20.55 | 8.00 | 48.00 | 8.20 | | 8.20 |
| 2675 | 48.56 | 38.00 | 48.00 | 2.57 | | 2.57 |
| 2690 | 44.41 | 42.00 | 48.00 | 0.85 | | 0.85 |
| 2702 | 46.49 | 42.00 | 48.00 | 0.95 | | 0.95 |
| 2705 | 48.50 | 44.00 | 48.00 | 0.27 | | 0.27 |
| 2729 | 46.55 | 46.00 | 48.00 | 1.50 | | 1.50 |
| 2739 | 46.24 | 46.00 | 48.00 | 8.98 | | 8.98 |
| 2740 | 48.23 | 46.00 | 48.00 | 3.07 | | 3.07 |
| 2742 | 44.24 | 44.00 | 48.00 | 2.04 | | 2.04 |
| 2756 | 46.56 | 40.00 | 50.00 | 15.17 | | 15.17 |
| 2760 | 50.50 | 44.00 | 50.00 | 3.04 | | 3.04 |
| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | TOTAL |
| 2778 | 50.57 | 20.00 | 50.00 | 27.04 | 13.31 | 40.35 |
| 2802 | 46.55 | 46.00 | 50.00 | 0.96 | | 0.96 |
| 2808 | 48.50 | 42.00 | 50.00 | 12.15 | | 12.15 |
| 2813 | 50.50 | 44.00 | 50.00 | 8.73 | | 8.73 |
| 2817 | 50.24 | 48.00 | 50.00 | 1.04 | | 1.04 |
| 2819 | 46.24 | 46.00 | 50.00 | 1.52 | | 1.52 |
| 2848 | 52.49 | 48.00 | 52.00 | 1.71 | | 1.71 |
| 2910 | 46.63 | 46.00 | 52.00 | 2.72 | | 2.72 |
| 2915 | 48.24 | 48.00 | 52.00 | 4.20 | | 4.20 |
| 2918 | 52.19 | 48.00 | 52.00 | 3.57 | | 3.57 |
| 2923 | 48.63 | 48.00 | 52.00 | 14.52 | | 14.52 |
| 2926 | 50.19 | 48.00 | 52.00 | 3.02 | | 3.02 |
| 2965 | 54.56 | 52.00 | 54.00 | 3.03 | | 3.03 |
| 3005 | 54.50 | 52.00 | 54.00 | 4.04 | | 4.04 |
| 3021 | 54.24 | 54.00 | 54.00 | 0.51 | | 0.51 |
| 3031 | 50.41 | 10.00 | 54.00 | 12.91 | | 12.91 |
| 3047 | 52.49 | 50.00 | 54.00 | 37.54 | | 37.54 |
| 3107 | 54.63 | 54.00 | 54.00 | 0.42 | | 0.42 |
| 3119 | 50.24 | 50.00 | 54.00 | 3.84 | | 3.84 |
| 3124 | 54.63 | 54.00 | 54.00 | 3.43 | | 3.43 |
| 3153 | 56.54 | 50.00 | 56.00 | 27.50 | | 27.50 |
| 3192 | 54.59 | 54.00 | 56.00 | 0.28 | | 0.28 |
| 3201 | 54.55 | 52.00 | 56.00 | 47.88 | | 47.88 |
| 3256 | 56.24 | 54.00 | 56.00 | 0.32 | | 0.32 |
| 3260 | 54.50 | 48.00 | 56.00 | 9.38 | | 9.38 |
| 3261 | 54.55 | 50.00 | 56.00 | 13.11 | | 13.11 |
| 3265 | 58.53 | 20.00 | 58.00 | 26.99 | | 26.99 |
| 3280 | 54.56 | 54.00 | 58.00 | 3.16 | | 3.16 |
| 3347 | 56.50 | 54.00 | 58.00 | 0.28 | | 0.28 |
| 3394 | 58.47 | 52.00 | 58.00 | 2.45 | | 2.45 |
| 3399 | 54.63 | 50.00 | 58.00 | 5.54 | | 5.54 |
| 3567 | 60.19 | 54.00 | 60.00 | 1.27 | | 1.27 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 3602 | 58.50 | 48.00 | 60.00 | 22.82 | | 22.82 |
| 3603 | 60.50 | 54.00 | 60.00 | 4.17 | | 4.17 |
| 3663 | 60.19 | 54.00 | 60.00 | 14.78 | | 14.78 |
| 3664 | 58.19 | 54.00 | 60.00 | 6.28 | | 6.28 |
| 3667 | 56.52 | 54.00 | 60.00 | 2.19 | | 2.19 |
| 3670 | 60.19 | 54.00 | 60.00 | 16.09 | | 16.09 |
| 3690 | 60.50 | 54.00 | 60.00 | 9.11 | | 9.11 |
| 3701 | 58.53 | 54.00 | 62.00 | 3.30 | | 3.30 |
| 3766 | 62.24 | 54.00 | 62.00 | 3.08 | | 3.08 |
| 3789 | 62.53 | 52.00 | 62.00 | 6.01 | | 6.01 |
| 3828 | 58.53 | 52.00 | 62.00 | 41.21 | | 41.21 |
| 3832 | 58.24 | 54.00 | 62.00 | 30.14 | | 30.14 |
| 3840 | 56.56 | 52.00 | 62.00 | 12.40 | | 12.40 |
| 3849 | 60.49 | 52.00 | 62.00 | 139.77 | | 139.77 |
| 3911 | 60.50 | 52.00 | 64.00 | 73.66 | | 73.66 |
| 3925 | 58.50 | 14.00 | 64.00 | 18.68 | | 18.68 |
| 3927 | 54.63 | 54.00 | 64.00 | 4.08 | | 4.08 |
| 3995 | 66.50 | 50.00 | 66.00 | 37.14 | | 37.14 |
| 4006 | 66.49 | 54.00 | 66.00 | 15.22 | | 15.22 |
| 4027 | 54.24 | 54.00 | 66.00 | 0.53 | | 0.53 |
| 4158 | 68.45 | 52.00 | 68.00 | 33.83 | | 33.83 |
| 4165 | 68.56 | 58.00 | 68.00 | 0.69 | | 0.69 |
| 4166 | 60.57 | 56.00 | 68.00 | 0.85 | | 0.85 |
| 4168 | 60.51 | 54.00 | 68.00 | 5.79 | | 5.79 |
| 4169 | 66.55 | 54.00 | 68.00 | 4.85 | | 4.85 |
| 4225 | 68.51 | 52.00 | 70.00 | 66.76 | | 66.76 |
| 4231 | 68.24 | 54.00 | 70.00 | 2.45 | | 2.45 |
| 4238 | 58.55 | 52.00 | 70.00 | 232.21 | | 232.21 |
| 4254 | 62.54 | 54.00 | 70.00 | 2.74 | | 2.74 |
| 4267 | 66.54 | 8.00 | 72.00 | 0.57 | | 0.57 |
| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | TOTAL |
| 4388 | 68.57 | 64.00 | 74.00 | 8.34 | | 8.34 |
| 4418 | 64.57 | 52.00 | 74.00 | 25.48 | | 25.48 |
| 4423 | 74.24 | 54.00 | 74.00 | 18.89 | | 18.89 |
| 4430 | 68.50 | 56.00 | 74.00 | 4.81 | | 4.81 |
| 4455 | 76.50 | 54.00 | 76.00 | 95.26 | | 95.26 |
| 4470 | 74.73 | 56.00 | 76.00 | 8.45 | | 8.45 |
| 4494 | 68.63 | 52.00 | 76.00 | 9.27 | | 9.27 |
| 4497 | 68.47 | 54.00 | 76.00 | 4.01 | | 4.01 |
| 4511 | 72.54 | 54.00 | 78.00 | 94.41 | | 94.41 |
| 4518 | 76.56 | 50.00 | 78.00 | 8.04 | | 8.04 |
| 4522 | 66.54 | 8.00 | 78.00 | 0.57 | | 0.57 |
| 4558 | 72.47 | 54.00 | 80.00 | 4.23 | | 4.23 |
| 4564 | 72.50 | 54.00 | 80.00 | 0.53 | | 0.53 |
| 4579 | 82.56 | 54.00 | 82.00 | 2.53 | | 2.53 |
| 4724 | 76.55 | 50.00 | 84.00 | 3.09 | | 3.09 |
| 4726 | 80.56 | 54.00 | 84.00 | 19.01 | | 19.01 |
| 4732 | 80.55 | 58.00 | 84.00 | 3.57 | | 3.57 |
| 4814 | 84.55 | 54.00 | 88.00 | 5.04 | | 5.04 |
| 4887 | 84.50 | 54.00 | 90.00 | 0.73 | | 0.73 |
| 5027 | 70.49 | 54.00 | 90.00 | 0.46 | | 0.46 |
| 5045 | 82.45 | 54.00 | 90.00 | 88.76 | | 88.76 |
| 5186 | 76.47 | 54.00 | 90.00 | 4.47 | | 4.47 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5206 | 82.50 | 54.00 | 90.00 | 26.84 | | 26.84 |
| 5243 | 72.49 | 50.00 | 90.00 | 110.52 | | 110.52 |
| 5286 | 84.57 | 54.00 | 90.00 | 205.40 | | 205.40 |
| 5289 | 66.54 | 8.00 | 90.00 | 5.70 | | 5.70 |
| 5299 | 84.49 | 44.00 | 90.00 | 25.52 | | 25.52 |
| 5304 | 66.50 | 52.00 | 90.00 | 1.98 | | 1.98 |
| 4270 | 62.57 | 52.00 | 72.00 | 24.58 | | 24.58 |
| 4277 | 72.49 | 54.00 | 72.00 | 26.34 | | 26.34 |
| 4366 | 60.59 | 60.00 | 74.00 | 0.05 | | 0.05 |
| TOTAL | | | | 4361.01 | 355.70 | 4716.71 |

2. Results using THRUPUT2.

| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | NO GO | TOTAL |
|---|---|---|---|---|---|---|---|
| 0199 | 4.63 | | 4.00 | 2.06 | | | 2.06 |
| 0204 | 4.58 | 4.00 | 4.00 | 0.12 | | | 0.12 |
| 0205 | 4.45 | 4.00 | 4.00 | 0.12 | | | 0.12 |
| 0206 | 4.47 | 4.00 | 4.00 | 0.12 | | | 0.12 |
| 0221 | 8.56 | 2.00 | 8.00 | 2.17 | | | 2.17 |
| 0223 | 6.41 | 2.00 | 8.00 | 0.29 | | | 0.29 |
| 0237 | 8.13 | 4.00 | 8.00 | 5.67 | | | 5.67 |
| 0239 | 6.48 | 4.00 | 8.00 | 50.19 | | | 50.19 |
| 0256 | 10.55 | 4.00 | 10.00 | 0.35 | | | 0.35 |
| 0260 | 6.41 | 4.00 | 10.00 | 0.44 | | | 0.44 |
| 0262 | 10.65 | 4.00 | 10.00 | 0.49 | | | 0.49 |
| 0264 | 10.13 | 4.00 | 10.00 | 0.18 | | | 0.18 |
| 0276 | 6.47 | 6.00 | 10.00 | 0.29 | | | 0.29 |
| 0278 | 6.63 | 4.00 | 10.00 | 4.78 | | | 4.78 |
| 0293 | 10.55 | 6.00 | 10.00 | 1.17 | | | 1.17 |
| 0332 | 10.65 | 8.00 | 10.00 | 0.19 | | | 0.19 |
| 0341 | 10.48 | 4.00 | 10.00 | 3.15 | | | 3.15 |
| 0353 | 6.78 | 6.00 | 10.00 | 55.25 | | | 55.25 |
| 0368 | 28.41 | 22.00 | 24.00 | 3.55 | 8.19 | | 11.74 |
| 0450 | 12.55 | 6.00 | 12.00 | 17.18 | | | 17.18 |
| 0459 | 12.66 | 8.00 | 12.00 | 3.44 | | | 3.44 |
| 0465 | 12.13 | 4.00 | 12.00 | 4.49 | | | 4.49 |
| 0467 | 12.13 | 8.00 | 12.00 | 0.43 | | | 0.43 |
| 0536 | 12.55 | 6.00 | 12.00 | 42.87 | | | 42.87 |
| 0571 | 8.08 | 8.00 | 12.00 | 3.04 | | | 3.04 |
| 0573 | 12.13 | 8.00 | 12.00 | 4.00 | | | 4.00 |
| 0575 | 12.13 | 8.00 | 12.00 | 2.46 | | | 2.46 |
| 0576 | 12.55 | 4.00 | 12.00 | 11.38 | | | 11.38 |
| 0580 | 12.55 | 6.00 | 12.00 | 7.01 | | | 7.01 |
| 0581 | 12.13 | 6.00 | 12.00 | 6.24 | | | 6.24 |
| 0651 | 14.66 | 8.00 | 14.00 | 6.17 | | | 6.17 |
| 0655 | 14.55 | 6.00 | 14.00 | 25.52 | | | 25.52 |
| 0658 | NA | 8.00 | 14.00 | 290.97 | | | 290.97 |
| 0761 | 14.37 | 8.00 | 14.00 | 2.73 | | | 2.73 |
| 0796 | NA | 8.00 | 14.00 | 91.14 | 14.23 | 39.68 | 145.05 |
| 0799 | 14.66 | 10.00 | 14.00 | 12.45 | | | 12.45 |
| 0887 | 16.55 | 8.00 | 16.00 | 37.18 | | | 37.18 |
| 0888 | 16.55 | 8.00 | 16.00 | 9.09 | | | 9.09 |
| 0907 | 16.13 | 8.00 | 16.00 | 2.31 | | | 2.31 |
| 0910 | 16.08 | 8.00 | 16.00 | 0.40 | | | 0.40 |
| 0940 | 16.55 | 8.00 | 16.00 | 14.61 | | | 14.61 |
| 0944 | 16.55 | 8.00 | 16.00 | 0.03 | | | 0.03 |
| 0953 | 16.55 | 8.00 | 16.00 | 57.02 | | | 57.02 |
| 0954 | 16.55 | 8.00 | 16.00 | 11.75 | | | 11.75 |
| 0984 | 18.55 | 8.00 | 18.00 | 22.14 | | | 22.14 |
| 1030 | 18.13 | 8.00 | 18.00 | 3.86 | | | 3.86 |
| 1032 | 18.08 | 8.00 | 18.00 | 1.92 | | | 1.92 |
| 1079 | NA | 8.00 | 18.00 | 263.48 | | | 263.48 |
| 1085 | 18.55 | 8.00 | 18.00 | 3.99 | | | 3.99 |
| 1173 | 20.13 | 6.00 | 20.00 | 21.33 | | | 21.33 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1195 | 20.66 | 8.00 | 20.00 | 1.10 | | | 1.10 |
| 1206 | 20.78 | 8.00 | 20.00 | 15.83 | | | 15.83 |
| 1210 | 20.55 | 8.00 | 20.00 | 10.24 | | | 10.24 |
| 1268 | 20.66 | 8.00 | 20.00 | 0.30 | | | 0.30 |
| 1271 | 20.37 | 8.00 | 20.00 | 9.18 | | | 9.18 |
| 1273 | 20.55 | 8.00 | 20.00 | 17.73 | | | 17.73 |
| 1290 | 20.55 | 8.00 | 20.00 | 15.62 | | | 15.62 |
| 1302 | 20.37 | 10.00 | 20.00 | 0.50 | | | 0.50 |
| 1312 | 20.55 | 8.00 | 20.00 | 46.29 | | | 46.29 |
| 1318 | 20.51 | 10.00 | 20.00 | 4.61 | | | 4.61 |
| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | NO GO | TOTAL |
| 1336 | 20.55 | 8.00 | 20.00 | 13.17 | | | 13.17 |
| 1349 | 20.13 | 16.00 | 20.00 | 3.46 | | | 3.46 |
| 1495 | NA | 8.00 | 22.00 | 246.32 | 196.52 | | 42.85 |
| 1497 | 22.55 | 10.00 | 22.00 | 49.53 | | | 49.53 |
| 1508 | 22.55 | 14.00 | 22.00 | 1.03 | | | 1.03 |
| 1519 | 24.13 | 4.00 | 24.00 | 0.54 | | | 0.54 |
| 1564 | 24.55 | 12.00 | 24.00 | 14.06 | | | 14.06 |
| 1619 | 24.55 | 8.00 | 24.00 | 4.80 | | | 4.80 |
| 1658 | 24.78 | 8.00 | 24.00 | 19.47 | | | 19.47 |
| 1670 | 28.78 | 8.00 | 24.00 | 14.63 | 52.40 | | 67.03 |
| 1692 | 24.55 | 10.00 | 24.00 | 12.15 | | | 12.15 |
| 1721 | 24.66 | 10.00 | 24.00 | 0.29 | | | 0.29 |
| 1756 | 24.55 | 10.00 | 24.00 | 16.35 | | | 16.35 |
| 1800 | 24.55 | 8.00 | 24.00 | 48.59 | | | 48.59 |
| 1842 | 24.55 | 8.00 | 24.00 | 5.76 | | | 5.76 |
| 1907 | 30.63 | 12.00 | 26.00 | | 160.61 | | 160.61 |
| 1908 | 26.55 | 12.00 | 26.00 | 14.09 | | | 14.09 |
| 1909 | 26.55 | 8.00 | 26.00 | 15.33 | | | 15.33 |
| 1941 | 28.13 | 4.00 | 28.00 | 0.49 | | | 0.49 |
| 1943 | 28.63 | 8.00 | 28.00 | 43.56 | | | 43.56 |
| 2024 | 30.55 | 8.00 | 30.00 | 0.56 | | | 0.56 |
| 2032 | 30.45 | 16.00 | 30.00 | 2.09 | | | 2.09 |
| 2069 | 32.63 | 20.00 | 32.00 | 27.94 | | | 27.94 |
| 2130 | 34.13 | 4.00 | 34.00 | 0.21 | | | 0.21 |
| 2135 | 34.63 | 10.00 | 34.00 | 2.54 | | | 2.54 |
| 2154 | 34.78 | 8.00 | 34.00 | 75.92 | | | 75.92 |
| 2158 | 34.63 | 16.00 | 34.00 | 4.74 | | | 4.74 |
| 2184 | 34.13 | 26.00 | 34.00 | 0.37 | | | 0.37 |
| 2190 | 34.63 | 20.00 | 34.00 | 2.26 | | | 2.26 |
| 2201 | 36.63 | 8.00 | 36.00 | 1.73 | | | 1.73 |
| 2259 | 38.63 | 16.00 | 38.00 | 128.60 | | | 128.60 |
| 2267 | 38.63 | 24.00 | 38.00 | 28.60 | | | 28.60 |
| 2268 | 38.13 | 28.00 | 38.00 | 0.37 | | | 0.37 |
| 2339 | 40.63 | 14.00 | 40.00 | 4.38 | | | 4.38 |
| 2342 | 40.63 | 28.00 | 40.00 | 13.82 | | | 13.82 |
| 2354 | 40.63 | 10.00 | 40.00 | 0.46 | | | 0.46 |
| 2355 | 40.63 | 24.00 | 40.00 | 1.25 | | | 1.25 |
| 2361 | 42.63 | 8.00 | 42.00 | 9.64 | | | 9.64 |
| 2390 | 42.78 | 8.00 | 42.00 | 34.27 | | | 34.27 |
| 2409 | 42.63 | 8.00 | 42.00 | 17.37 | | | 17.37 |
| 2423 | 42.63 | 36.00 | 42.00 | 0.26 | | | 0.26 |
| 2484 | 44.63 | 18.00 | 44.00 | 122.48 | | | 122.48 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2565 | 48.78 | 10.00 | 48.00 | 7.17 | | | 7.17 |
| 2625 | 48.64 | 44.00 | 48.00 | 3.95 | | | 3.95 |
| 2628 | 48.22 | 44.00 | 48.00 | 0.81 | | | 0.81 |
| 2637 | 50.40 | 8.00 | 50.00 | 0.55 | | | 0.55 |
| 2658 | 50.56 | 14.00 | 50.00 | 1.02 | | | 1.02 |
| 2661 | 50.63 | 8.00 | 50.00 | 8.19 | | | 8.19 |
| 2675 | 44.54 | 38.00 | 50.00 | 2.56 | | | 2.56 |
| 2690 | 50.63 | 42.00 | 50.00 | 0.85 | | | 0.85 |
| 2702 | 48.53 | 42.00 | 50.00 | 0.95 | | | 0.95 |
| 2705 | 50.59 | 44.00 | 50.00 | 0.27 | | | 0.27 |
| 2729 | 50.64 | 46.00 | 50.00 | 1.48 | | | 1.48 |
| 2739 | 50.24 | 46.00 | 50.00 | 8.98 | | | 8.98 |
| 2740 | 50.24 | 46.00 | 50.00 | 3.07 | | | 3.07 |
| 2742 | 50.24 | 44.00 | 50.00 | 2.04 | | | 2.04 |
| 2756 | 50.64 | 40.00 | 50.00 | 15.17 | | | 15.17 |
| 2760 | 50.64 | 44.00 | 50.00 | 3.04 | | | 3.04 |
| 2778 | 52.63 | 20.00 | 52.00 | 27.04 | | | 27.04 |
| 2802 | 52.64 | 46.00 | 52.00 | 0.96 | | | 0.96 |
| 2808 | 52.64 | 42.00 | 52.00 | 12.15 | | | 12.15 |
| 2813 | 52.64 | 44.00 | 52.00 | 8.72 | | | 8.72 |

| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | NO GO | TOTAL |
|---|---|---|---|---|---|---|---|
| 2817 | 52.22 | 48.00 | 52.00 | 1.04 | | | 1.04 |
| 2819 | 52.22 | 46.00 | 52.00 | 1.52 | | | 1.52 |
| 2848 | 52.64 | 48.00 | 52.00 | 1.71 | | | 1.71 |
| 2910 | 54.63 | 46.00 | 54.00 | 2.72 | | | 2.72 |
| 2915 | 54.24 | 48.00 | 54.00 | 4.20 | | | 4.20 |
| 2918 | 54.24 | 48.00 | 54.00 | 3.57 | | | 3.57 |
| 2923 | 54.64 | 48.00 | 54.00 | 14.52 | | | 14.52 |
| 2926 | 54.23 | 48.00 | 54.00 | 3.02 | | | 3.02 |
| 2965 | 54.64 | 52.00 | 54.00 | 3.03 | | | 3.03 |
| 3005 | 54.64 | 52.00 | 54.00 | 4.04 | | | 4.04 |
| 3021 | 54.24 | 54.00 | 54.00 | 0.51 | | | 0.51 |
| 3031 | 56.63 | 10.00 | 56.00 | 12.91 | | | 12.91 |
| 3047 | 56.59 | 50.00 | 56.00 | 37.54 | | | 37.54 |
| 3107 | 56.64 | 54.00 | 56.00 | 0.42 | | | 0.42 |
| 3119 | 56.24 | 50.00 | 56.00 | 3.84 | | | 3.84 |
| 3124 | 56.64 | 54.00 | 56.00 | 3.44 | | | 3.44 |
| 3153 | 56.64 | 50.00 | 56.00 | 27.50 | | | 27.50 |
| 3192 | 56.59 | 54.00 | 56.00 | 0.28 | | | 0.28 |
| 3201 | 58.64 | 52.00 | 58.00 | 47.89 | | | 47.89 |
| 3256 | 58.24 | 54.00 | 58.00 | 0.32 | | | 0.32 |
| 3260 | 58.64 | 48.00 | 58.00 | 9.39 | | | 9.39 |
| 3261 | 58.64 | 50.00 | 58.00 | 13.12 | | | 13.12 |
| 3265 | 58.63 | 20.00 | 58.00 | 26.99 | | | 26.99 |
| 3280 | NA | 54.00 | 58.00 | | | 3.16 | 3.16 |
| 3347 | 58.63 | 54.00 | 58.00 | 0.28 | | | 0.28 |
| 3394 | 60.63 | 52.00 | 60.00 | 2.46 | | | 2.46 |
| 3399 | 60.63 | 50.00 | 60.00 | 5.54 | | | 5.54 |
| 3567 | 60.24 | 54.00 | 60.00 | 1.27 | | | 1.27 |
| 3602 | 60.64 | 48.00 | 60.00 | 22.83 | | | 22.83 |
| 3603 | 60.64 | 54.00 | 60.00 | 4.18 | | | 4.18 |
| 3663 | 62.24 | 54.00 | 62.00 | 14.78 | | | 14.78 |
| 3664 | 62.24 | 54.00 | 62.00 | 6.28 | | | 6.28 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3667 | 62.59 | 54.00 | 62.00 | 2.19 | | | 2.19 |
| 3670 | 62.24 | 54.00 | 62.00 | 16.09 | | | 16.09 |
| 3690 | 62.64 | 54.00 | 62.00 | 9.13 | | | 9.13 |
| 3701 | 62.64 | 54.00 | 62.00 | 3.31 | | | 3.31 |
| 3766 | 62.24 | 54.00 | 62.00 | 3.08 | | | 3.08 |
| 3789 | 64.64 | 52.00 | 64.00 | 6.02 | | | 6.02 |
| 3828 | 64.64 | 52.00 | 64.00 | 41.23 | | | 41.23 |
| 3832 | 64.22 | 54.00 | 64.00 | 30.14 | | | 30.14 |
| 3840 | 64.64 | 52.00 | 64.00 | 12.42 | | | 12.42 |
| 3849 | 64.64 | 52.00 | 64.00 | 139.78 | | | 139.78 |
| 3911 | NA | 52.00 | 64.00 | 73.66 | | | 73.66 |
| 3925 | 66.63 | 14.00 | 66.00 | 18.68 | | | 18.68 |
| 3927 | 66.64 | 54.00 | 66.00 | 4.07 | | | 4.07 |
| 3995 | 66.64 | 50.00 | 66.00 | 37.14 | | | 37.14 |
| 4006 | 68.64 | 54.00 | 68.00 | 15.23 | | | 15.23 |
| 4027 | 68.24 | 54.00 | 68.00 | 0.53 | | | 0.53 |
| 4158 | 70.64 | 52.00 | 70.00 | 33.86 | | | 33.86 |
| 4165 | 70.57 | 58.00 | 70.00 | 0.69 | | | 0.69 |
| 4166 | 70.57 | 56.00 | 70.00 | 0.84 | | | 0.84 |
| 4168 | 70.64 | 54.00 | 70.00 | 5.79 | | | 5.79 |
| 4169 | 70.64 | 54.00 | 70.00 | 4.87 | | | 4.87 |
| 4225 | 70.64 | 52.00 | 70.00 | 66.77 | | | 66.77 |
| 4231 | 72.24 | 54.00 | 72.00 | 2.45 | | | 2.45 |
| 4238 | NA | 52.00 | 72.00 | 97.48 | | 134.73 | 232.21 |
| 4254 | 72.64 | 54.00 | 72.00 | 2.73 | | | 2.73 |
| 4267 | 72.64 | 8.00 | 72.00 | 0.55 | | | 0.55 |
| 4270 | 72.64 | 52.00 | 72.00 | 24.56 | | | 24.56 |
| 4277 | 72.64 | 54.00 | 72.00 | 26.35 | | | 26.35 |
| 4366 | 72.64 | 60.00 | 74.00 | 0.07 | | | 0.07 |
| 4388 | 74.63 | 64.00 | 74.00 | 8.34 | | | 8.34 |
| | CLOSEDATE | ALD | RDD | ON TIME | LATE DELIV | NO GO | TOTAL |
| 4418 | 76.64 | 52.00 | 76.00 | 25.50 | | | 25.50 |
| 4423 | 76.24 | 54.00 | 76.00 | 18.89 | | | 18.89 |
| 4430 | 76.64 | 56.00 | 76.00 | 4.80 | | | 4.80 |
| 4455 | 76.64 | 54.00 | 76.00 | 95.26 | | | 95.26 |
| 4470 | 76.73 | 56.00 | 76.00 | 8.45 | | | 8.45 |
| 4494 | 78.64 | 52.00 | 78.00 | 9.26 | | | 9.26 |
| 4497 | 78.64 | 54.00 | 78.00 | 4.01 | | | 4.01 |
| 4511 | NA | 54.00 | 78.00 | 54.68 | 36.48 | 3.24 | 94.41 |
| 4518 | 78.64 | 50.00 | 78.00 | 8.05 | | | 8.05 |
| 4522 | 78.64 | 8.00 | 80.00 | 0.55 | | | 0.55 |
| 4558 | 80.63 | 54.00 | 80.00 | 4.23 | | | 4.23 |
| 4564 | 82.64 | 54.00 | 82.00 | 0.60 | | | 0.60 |
| 4579 | 82.64 | 54.00 | 82.00 | 2.53 | | | 2.53 |
| 4724 | 84.55 | 50.00 | 84.00 | 3.14 | | | 3.14 |
| 4726 | 86.63 | 54.00 | 84.00 | 17.45 | 1.55 | | 19.01 |
| 4732 | 84.64 | 58.00 | 84.00 | 3.55 | | | 3.55 |
| 4814 | 88.64 | 54.00 | 88.00 | 5.04 | | | 5.04 |
| 4887 | 90.64 | 54.00 | 90.00 | 0.76 | | | 0.76 |
| 5027 | 90.64 | 54.00 | 90.00 | 0.59 | | | 0.59 |
| 5045 | 90.64 | 54.00 | 90.00 | 88.77 | | | 88.77 |
| 5186 | 90.64 | 54.00 | 90.00 | 4.46 | | | 4.46 |
| 5206 | 90.64 | 54.00 | 90.00 | 26.85 | | | 26.85 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5243 | 90.64 | 50.00 | 90.00 | 110.51 | | | 110.51 |
| 5286 | 94.64 | 54.00 | 90.00 | 50.71 | 154.69 | | 205.39 |
| 5289 | 90.63 | 8.00 | 90.00 | 5.73 | | | 5.73 |
| 5299 | 90.64 | 44.00 | 90.00 | 25.53 | | | 25.53 |
| 5304 | 90.63 | 52.00 | 90.00 | 1.99 | | | 1.99 |
| TOTAL | | | | 3896.14 | 624.68 | 180.82 | 4701.64 |

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